Concept: A Muon Storage/Decay Ring at Fermilab

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Abstract

This note describes the concept of a muon decay/storage ring on the Fermilab site. Muons are created using 8 GeV proton beam and the existing AP0 target station. The ring is assumed to be racetrack-shaped with a straight section aimed at the MiniBooNE detector. Initially, Booster proton beam will be used, but the concept assumes that in the future, the 8 GeV protons will come from Project X. The initial estimate for 8 GeV protons is that ~10^{-3} pions of 2 GeV energy can be produced into 0.1 steradians in the forward direction per proton. This beam can be captured and stored with not much effort so that just using the Booster beam we can have ~10^{11} muons per second stored.

Introduction

In an attempt to create more opportunities for beam-based experiments using existing Fermilab infrastructure and in the light of recently expressed interest in short-baseline neutrino experiments, we propose to build a racetrack-shaped muon storage/decay ring. The idea is to use the existing target station and MiniBooNE detector to reduce the construction time and cost of the project. The long straight of the racetrack is directed toward the MiniBooNE detector. The ring is positioned near the AP0 target station and pions are injected into the straight section of the racetrack. Pions are produced using 8 GeV Booster beam and the existing pbar target station. Proton beam from the Booster is first injected into the Recycler, and the Booster batch is broken into four trains ~300 ns long, using the barrier-bucket system, with ~100 ns gap, as already proposed for the g-2 experiment. Each of the four trains is extracted using a ~60-ns-rise-time kicker. The racetrack is ~120 meters long and single-turn injection is assumed. The layout of the facility on the site is shown in Figure 1.

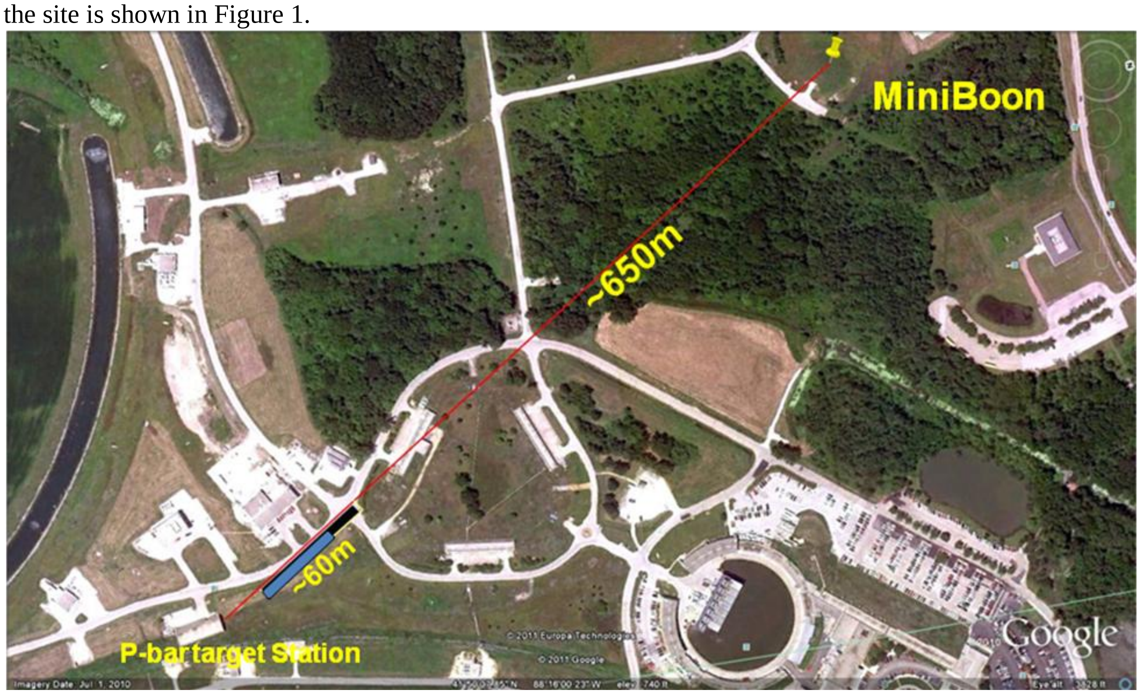


Figure 1: Fermilab Antiproton Complex, with racetrack storage/decay ring depicted as blue box. The red line indicates direction of neutrino beam that hits MiniBooNE detector.

In the remainder of this note we describe each stage of beam delivery/creation in more detail.

Proton Beam

In the initial stage we assume that 8 GeV proton beam from the Booster will be used. As proposed for the g-2 experiment, a Booster batch will be stored in the Recycler and, using a barrier-bucket system, separated into four trains, each ~300 ns long, with a ~100 ns gap for extraction. Each train will be separately extracted and targeted using the existing target station in AP0. We have also envisioned that the present design can use Project X beam without any modification. The proton beam from Project X will be injected into the Recycler with a chopped structure, so the barrier bucket system will not be needed. Assuming that the Recycler can store 5×10^{13} protons, it is clear that this part of the complex will not be a restricting element.

Target, Pion Capture

As already stated, our intention is to use the existing AP0 target station for pion/muon production. Presently pbars are produced using 120 GeV beam and a lithium lens, with an average beam power of ~70 kW. Assuming the target is made from Be, it is simple to estimate number of pions produced, using Striganov's formula:

For pions of $p = 2 \pm 0.1$ GeV/c produced at angles smaller than 0.1 radian, the number of pions per incident proton on a Be target is given by

$$N_p = e^{-x/\lambda\_Be} \frac{a}{b}(1 - e^{-b\theta^2}) \ ,$$

	a	b
π^+	0.48	22.57
π^-	0.3	18.91

where x is length of target and λ_Be is the 0.42 m interaction length of beryllium.

As shown in Fig. 2, the pbar target vault has limited space, so the Be target and quadrupole-triplet collection system must be designed to fit within the 2.5 meter space before the shielding block. The beam pipe radius is limited by the 40-mm-radius hole in the center of the shielding wall.

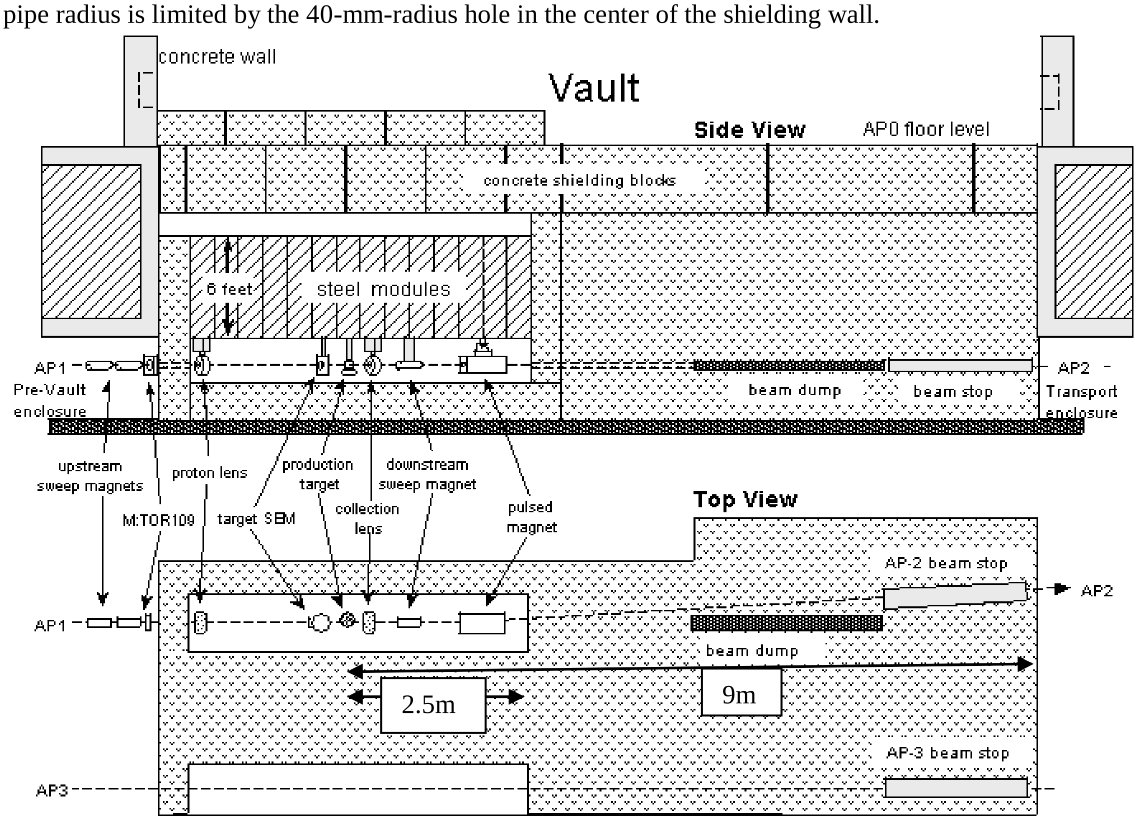


Figure 2: The target and focusing triplet must fit within a 2.5-meter-long space.

Also, the beam has to travel about 6.5 meters with a size less then 80 mm in the middle of the shielding wall. Figure 3 shows results from a Trace3D simulation of the beam transport, starting from the Be target and ending at the entrance to the storage ring.

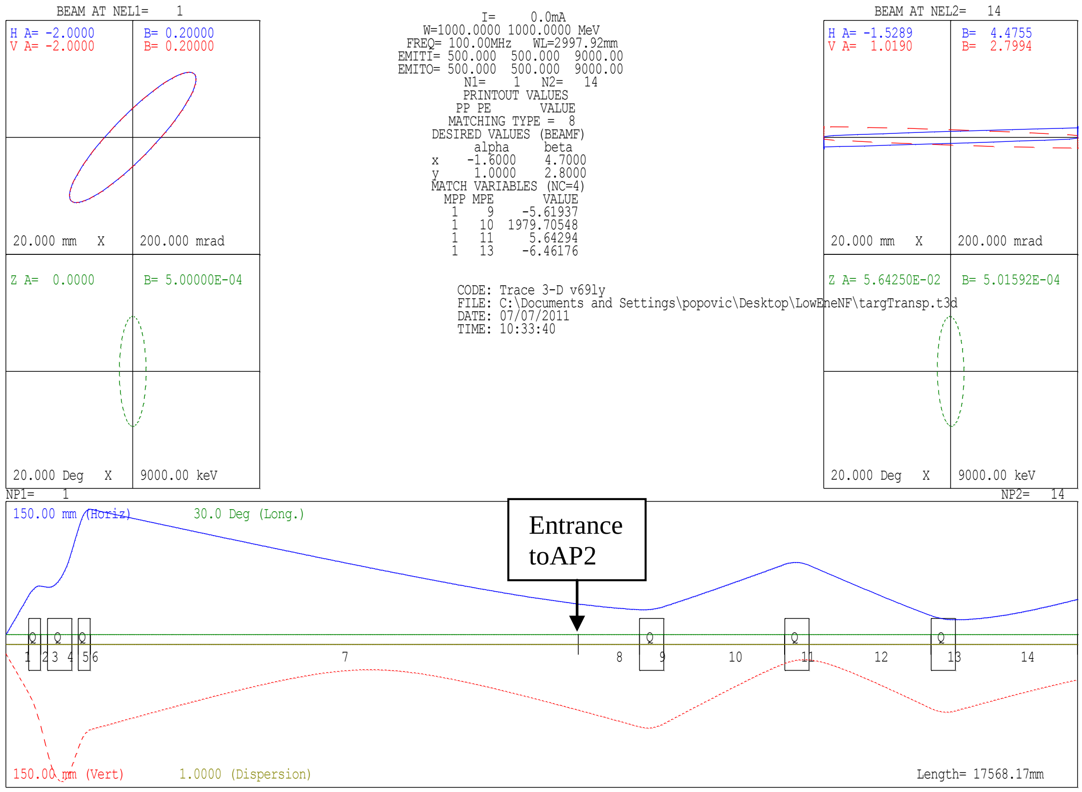


Figure 3: Trace3D simulations results for pion-beam transport to storage ring.

Pion Transport and Injection

Once the pions enter the AP2 enclosure there will be a system of quads to transport and inject these into the storage ring. We should allow about eight meters of transport from the target-shielding exit wall for injection into the ring. We assume that the last bending magnet in the arc will be used to bend the beam into the ring as indicated in Figure 4. To match the beam we use three quadrupoles, of the same type that will be used in the storage ring.

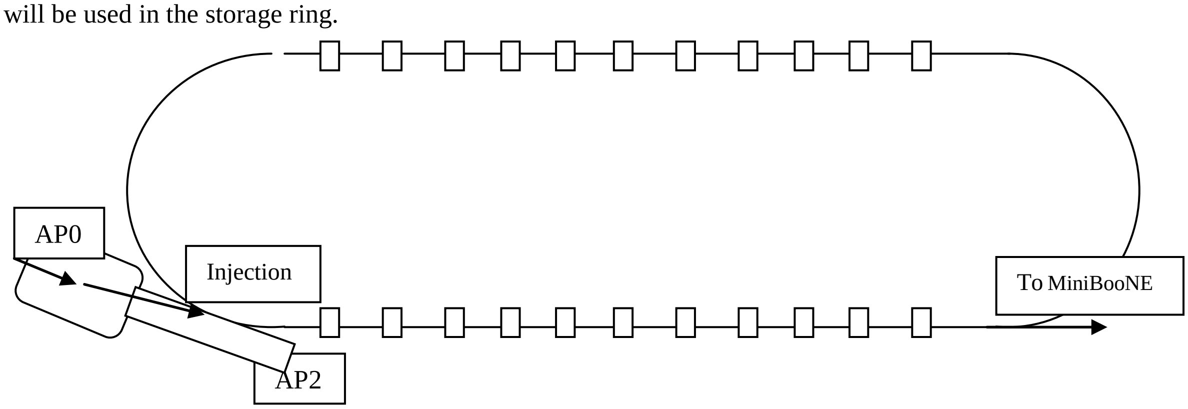


Figure 4. Storage/decay ring schematic.

Racetrack Storage Ring

The racetrack storage ring has two straight sections 50 meters long. The lattice is a simple FODO with arcs 10 meters long and dispersion canceled inside the arcs. Figure 5 shows the Trace3D display showing half of the ring, starting from half of the straight section with one arc and half of the other straight section.

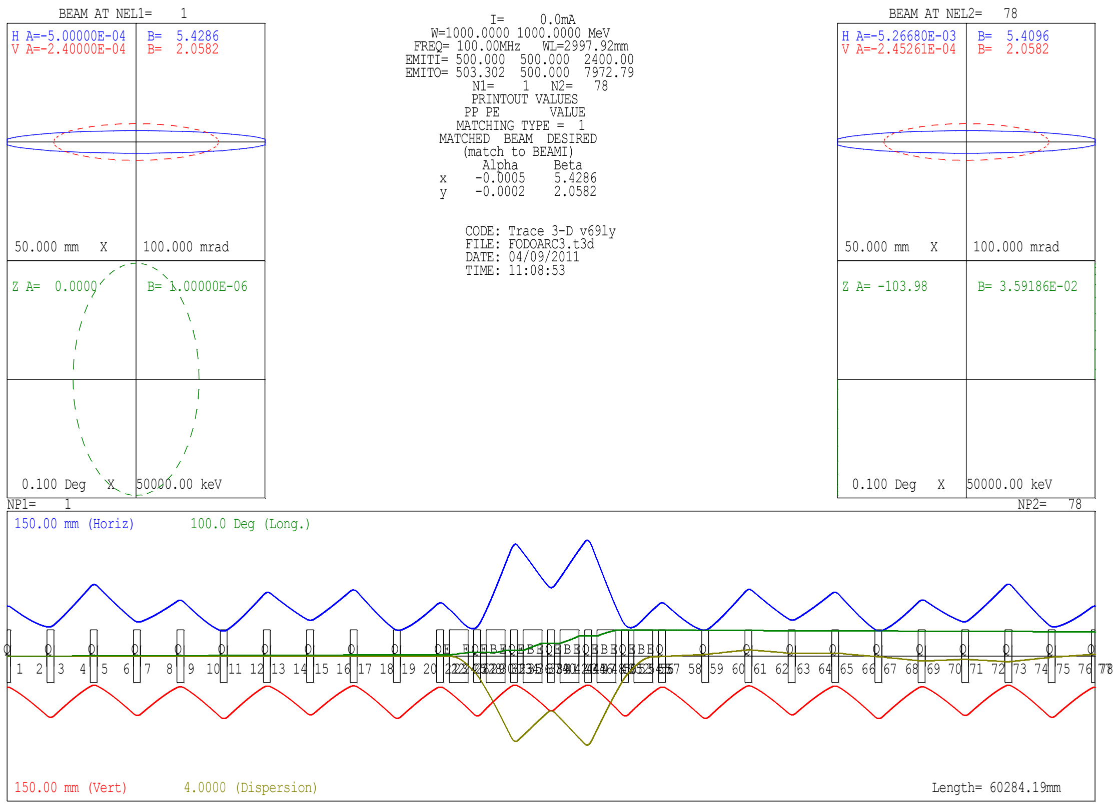


Figure 5: Blue and red are horizontal and vertical envelopes.

The table below summarizes the parameters of the racetrack elements.

Element	
Drifts in straights	2m
Dipole radius, gap, field, angle	R = 2 m, h = 0.15 m, B = 1.85 T, angle = 30°
Drift in arcs	0.3 m
Quad Length, Aperture, Gradient	L = 0.4 m, r = 0.15 m, g = 5 T/m
Quads total number	$50 = (2 \times 20 + 2 \times 5)$
Dipole total number	12
Total Length = Arc Lengths + Straights	120 m $= (2 \times 10 + 2 \times 50)$ m

Cost

Since the suggested facility is simple and based on existing technology, costing it is relatively simple. The costing is based on the costs of other projects at Fermilab:

Civil construction:

- Two tunnels 3 meters wide each, 30 k$ × 2 × 65 = ~4 M$
- Service building, 2 M$

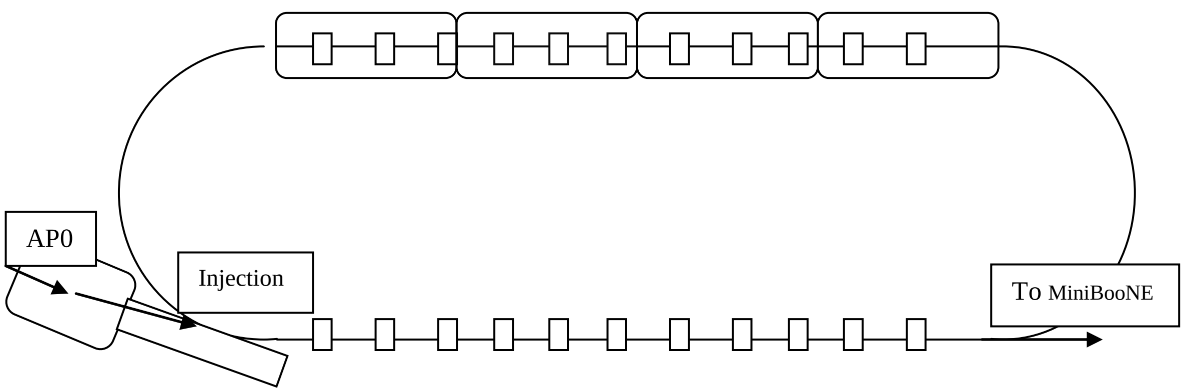
Components:

- 12 dipoles plus 2 spares @ 60 k$ per magnet = 0.84 M$
- 50 quads in the ring plus 10 for the transfer line plus spares @ 40 k$ per magnet = 2.4 M$
- Power supplies 70 × 10 k$ = 0.7 M$

All this is summarized in the following table.

Item	Cost in M$
Tunnel	4.00
Building	2.00
Dipoles	0.84
Quads	2.40
Power Supplies	0.70
Other, pipe, cables, ???	2.06
Total	12.00
Contingency+???	8.00
Grand Total	**20.00**

Future Improvements – Acceleration



Considering possible future improvements, we can think of accelerating the muon beam to an energy higher than the collection energy. One possibility is to use four Project X 650 MHz $\beta = 0.9$ cryomodules and install them in the return straight section. The injected pion beam is assumed to be DC, RF is on in the modules, and the path length of the beam is adjusted so that the beam gets bunch in the first few turns. When acceleration is needed, a fast three-bump is created so that the beam path is elongated. Then the incoming beam in the RF cavities attains a phase of 90°, the phase needed for acceleration. With four Project X cryomodules, the muon beam energy can be increased by up to 1 GeV per single pass.

Conclusions

We believe that a muon storage/decay ring can be built quickly, utilizing both the pbar target station and the MiniBooNE detector, and will cost under 20 M$. The building of the facility will have little or no impact on the running of planned experiments. The storage ring can be built to run at ~3 GeV/c muon momentum and can be used as an injector for the g-2 experiment. This will decouple g-2 from the pbar rings and the mu2e experiment, and will allow running both experiments in parallel, in addition to enabling a short-baseline neutrino program at Fermilab.